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Commentary

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A Birds-Eye View on Quantum Mechanics in Biology – the Entanglement Issue

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The Life of Facts

Nowadays there is an increasing amount of controversies and implications of a contemporary scientific fetish to the fundamentals of several biologists' research activities: quantum mechanics. Pivotal to this story is the dispute between the largely accepted fact that quantum mechanics lies at the heart of all micro and nano-world phenomena, and its role played in biology.

Quantum mechanics, however, is certainly the best theory of nature with the exception of gravity, explaining all known phenomena from atoms to condensed matter properties, and, furthermore, to an unprecedented level of accuracy. Its role in biology is played out in many ways. For instance, every chemical process relies on (as does biology) quantum mechanics by means of the so-called "trivial" quantum effects (e.g. electron orbitals and level transitions), known now for more than a half-century [1]. Such impressive confirmation of the universality of quantum laws, as now demonstrated by the detection of quantum entanglement between systems separated by km distances [2], extends the reach of quantum mechanics beyond the micro-world, increasing the appeal of quantum biology as a reputable field of study.

It has been argued for some time that a hot and wet biological environment limits or destroys subtle, non-obvious quantum effects (coherence, tunneling, entanglement, etc.). Recent evidence, however, suggests that a variety of organisms may harness some of the unique, non-trivial features of quantum mechanics thus gaining a biological advantage over classical equivalents. Results for non-trivial quantum effects in photosynthetic light harvesting, avian magneto reception and several other candidates for functional quantum biology was discussed by Lambert et al. [3].

Regarding light harvesting in photosynthesis, Sarovar and collaborators [4] presented strong evidence for entanglement observation in a protein structure that is central to photosynthesis by green anoxygenic bacteria. *This constitutes the first rigorous quantification of entanglement in a biological system [4-sic].*Interestingly, Scholes argues that [5] *"nature's solar cells have been improved through billions of years of evolution. It is therefore not so surprising that plants, algae, and other photosynthetic organisms have developed tricks that lie behind their success. It has emerged recently that one of these strategies, at least for some organisms, is to use quantum coherence to direct energy flow from molecule to molecule through antenna proteins. Natural light-harvesting antenna systems are a prominent component in the photosynthetic machinery".*

More trivially, there is a plethora of evidence showing that tunneling occurs in enzymes and that, most importantly, tunneling can speed up a reaction by a thousand times or more. As pointed out elsewhere, some enzymes seem to adjust the amount of tunneling to suit their operating temperature [6]. For details, followed by a vivid and conceptually formal discussion, the reader is referred to [7] and [3] and references therein.

Entanglement / Non-locality – the "Spooky" Quantum Mechanics

Quantum entanglement is a phenomenon imposing a correlation between two or more objects, such that one of them is unable to be precisely described should its counter-part (its mate) not taken into account. This leads to very strong correlations among the physical properties of the observables (as e.g. spins). As a consequence, measurements in one of the objects seem to instantaneously influence the other entangled objects, thus suggesting that such an "influence" would be instantaneously propagating, even among objects separated by arbitrarily large distances. It is said that such interaction is mediated by a "nonlocal" potential [8,9].

Albert Einstein, in 1935, referred to this nonlocal potential as a "spooky action at a distance" [10]. Since then, however, all the counter-intuitive predictions of quantum mechanics have been experimentally verified and non-locality is nowadays recognized as the most characteristic feature of so-called "non-trivial" quantum mechanics.

The Cell Interior – DNA-Proteins Interaction

The cell is a key example of a biological system using quantum mechanics to perform tasks unable to be done classically, as outlined below.

One of these tasks, of paramount importance for the protection and maintenance of life, is repair of DNA damage. Regarding DNA damage, double-strand breaks (DSB) are of great concern as they are not usually well repaired, eventually leading to inborn diseases or cancer [11].

After infliction of a DSB in DNA the protein kinase ATM (located outside the cell nucleus) is instantaneously activated by auto-phosphorylation. Following ATM activation, phosphate groups are added (phosphorylation) to several target proteins, responsible for the DSB repair completion. An appraisal of this repairing process on classical grounds has raised many questions so far unanswered [12]. The most relevant being:

(1) How ATM instantaneously senses the disruption of structure directly in 'relaxed' chromatin? No mediators are involved.

(2) Why proteins throughout the cell nucleus respond in a coordinated way, and how a few DSBs within three billion base pairs are recognized?

(3) What factors determine the impressive speed and extent of the ATM response?

It is clear that information transmission takes place, the key ingredient in DNA–protein interaction. Regarding the nature of this process, two "obvious" following possibilities may be excluded: signal transmission either by diffusion or electromagnetic interaction. As a matter of fact, cell interior is poorly insulated and bathed in a conductive medium (cytoplasm). Rather, the cell nucleus is a tangled mess, as vividly depicted by Philip Ball in his *Portrait of a molecule* [13].

As a consequence, a signal would suffer serious degradation due to dissipation by resistive losses, thus making DNA–protein signaling unviable. This puzzle can be overcome on the grounds of known, although counterintuitive, "non trivial" quantum principles.

DNA-Protein Entanglement – Beyond Classical and/or Trivial Quantum Effects

Rieper et al. [14] formulated a model for electron clouds of DNA nucleic acid components as coupled quantum harmonic-oscillator chains. It was assumed dipole-dipole interactions between an oscillator-chain with its neighbouring counterparts [15], providing a satisfactory account for the so-called van der Waals bonds. Interestingly, highlighting the occurrence of quantum entanglement between the electron clouds, even at room temperature.

Partially based on these theoretical results, particularly a suggestion for the use of dipole-dipole interactions in a harmonic oscillator-chain [14,15], researchers of the USP-Ítalo-Instec collaboration (University of Sao Paulo, Italy-Brazilian University Center and Higher Institute of Technologies and Applied Sciences/Cuba) are currently working out a model for DNA–protein interaction in terms of quantum entanglement. The leading hypothesis of this model is the well accepted fact that an entanglement state between two objects exists when: (1) they share a common structure, and/or (2) their structures were in contact at some moment.

Under these circumstances, the likely possibility for the occurrence of entanglement between a protein and the DNA would be determined by the seminal correlation between these two objects – proteins are products of RNA which, in turn, is a product of DNA. In fact, the first condition for entanglement (the sharing of a common structure) is fulfilled by DNA and its expressed proteins, since the assembling of amino acids uses the information codified in the genes.

More specifically, the above mentioned model proposes for DNA–ATM interaction the following Hamiltonian [16]

Where Vi,dip-dip and $V^{DNA\text{-}ATM}$ are dipole-dipole potentials describing the interaction between DNA's nucleotides and between every single nucleotide at DNA's chain and ATM, respectively. N, number of nucleotide bases of the DNA chain; d, chain size; m, electronic cloud mass in each nucleotide base; M, electronic cloud mass of ATM; Ωi,d, trapping potentials. Preliminary results to appear soon indicate that DNA-ATM entanglement would be feasible at distances over 100 nm and at physiological temperatures [16].

Thus, the entanglement between the DNA strands and the monomers of the protein ATM would establish an instantaneous DNA-ATM communication without the need for "messengers" (without energy transfer). Within such a "nonlocal" scenario, all the unanswered questions associated with the repair of DSB (see above) would be neatly addressed.

Final Remarks

It is difficult to explain many biological processes at molecular level in terms of classical principles. This shortcoming suggests that the structure of living matter, as described by most of the approaches employed in biology, is inadequate. In fact, life is a final and sophisticated product elaborated by the quantum nature of inanimate matter. Actually, the 'new orthodoxy' in the physics foundations presumes all nature quantum (i.e., that all natural phenomena are most completely and adequately described quantum-mechanically), whereas classical physics provides only a rough approximation. But, by no means is biology simply applied quantum mechanics.

Quantum mechanics does not show what nature will provide, but does point to the behavior of anything that can be defined and specified, either as a particle or as a wave. This is established by the De Broglie dual wave–particle equation, the fundamental equation of quantum mechanics.

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